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A Masterclass in Interdisciplinarity: Research into Practice in Training the Next Generation of Interdisciplinary Researchers

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A Masterclass in Interdisciplinarity: Research into practice in training the next generation of interdisciplinary researchers

Abstract

This paper draws on evaluations of a number of interdisciplinary studentship and fellowship schemes to discuss some of the challenges of developing interdisciplinary research skills in early career researchers. It describes efforts to support such capacity-building in the UK through a series of Interdisciplinary Masterclasses which used workshop-based elicitation techniques to develop smallscale studies in order to synthesise experiential knowledge and foster mutual learning. This has enabled us to build important bridges between research and practice, thereby supporting and developing the interdisciplinary careers of early- and mid-career researchers, as well as research managers and leaders. This paper describes an approach to interdisciplinary capacity-building derived from actual practice. Based on learning from these activities, we offer some suggestions for improved supervision and mentoring of interdisciplinary graduate students and young postdoctoral researchers. If we are to develop effective, future interdisciplinary capacity, we advocate that supervisors/mentors need to focus, not just on the research, but on the particular forms of professional support and mentoring required by inexperienced interdisciplinary researchers in terms of career guidance, the development of publications strategies and network building.

1. Introduction

The continuing emphasis on interdisciplinarity, especially that which integrates the social and natural sciences, requires academic researchers to collaborate across disciplinary, epistemic and methodological boundaries. Much has been learnt through international experiences (for example, [1]) and through publicly-funded research initiatives in the UK about what is entailed in the practice of interdisciplinarity and the challenges of building an academic interdisciplinary research career but efforts to nurture interdisciplinary research teams and centres still lead universities to seek to reduce the transaction costs of such work [2]. There is a growing body of knowledge within the futures field, and elsewhere, which describes and theorises what inter- and trans-disciplinarity does or should entail, which addresses the challenges and quandaries that such researchers face and which highlights the problems of evaluating the quality of such research (for example, [3-5]). Nevertheless, despite long-standing and increasingly insistent calls from national and supra-national funders (for example, [6-11]) for interdisciplinary and, increasingly, transdisciplinary research as a means to promote scientific and technological advance (resulting in innovation-led economic competitiveness) and to foster its more effective acceptance and beneficial utilisation in society, disciplinary research and teaching still predominate in academia.

Interdisciplinary scholars face both "the difficult prospect of imagining and enacting schemas to shape, support and evaluate this dynamic approach to research" [5] and the resistance to interdisciplinarity (especially to that which is issue- or problem-oriented) within the academic world, leaving the status of graduate students and junior faculty who pursue interdisciplinary work, in particular, vulnerable to criticism [4].

If we accept that "[O]urs is a time of both ontological and epistemological revolution" where "[A]lmost all the problems we face nowadays are complex, interconnected, contradictory, located in an uncertain environment and embedded in landscapes that are rapidly changing" [12], then we must expect the future of research to be increasingly interdisciplinary. This

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would imply the desirability of focusing some attention both on the characteristics of such work, and also on what might be required to foster and encourage it [4]. However, from a UK perspective at least, interdisciplinary training is not yet fully addressed within our graduate teaching and there has been very little emphasis on how we grow future talent so that the next generation of inter- and trans-disciplinary researchers is better equipped to face these challenges. One fruitful approach may be to improve research training and research mentoring for interdisciplinary researchers, especially those in the formative stages of their interdisciplinary career.

This paper synthesises our experiences of conducting, facilitating and evaluating interdisciplinary research in the UK. This programme of research has developed from early work that sought to capture the dynamics of interdisciplinary research, such as Bruce et al. [13] which identified some of the barriers to interdisciplinary integration within the European Union 5th Framework Programme, to more recent studies [14] which identified some of the strategies used by successful interdisciplinary researchers to overcome these. On the basis of this experience, we have been invited by the UK Research Councils to conduct a number of evaluations and learning reviews of interdisciplinary funding initiatives designed to support early career researchers (ECRs) (for example, [15,16]).

A key element of our research strategy has always been to encourage research participants to reflect on their interdisciplinary experiences as a way of bringing research insights most effectively into practice. We have used focus groups and workshop-based elicitation techniques to develop small-scale studies in order to synthesise experiential knowledge and foster mutual learning. We have extended this reflexivity into our training of interdisciplinary researchers at all levels and have been able to co-produce knowledge in collaboration with key stakeholders. This has enabled us to support the interdisciplinary careers of early- and mid-career researchers, as well as research managers and leaders, and this has built important bridges between research and practice. This paper therefore describes an approach to interdisciplinary capacity-building derived from actual practice.

Supervisors and mentors have a key role to play in advising and guiding PhD students and junior colleagues at the beginning of an interdisciplinary career. In particular, finding an intellectual community can be a major contributing factor to student success by countering the potential feeling of intellectual homelessness [17] among those not firmly embedded within one discipline. This paper begins by considering what funders and other institutions are doing to develop interdisciplinary research capacity through publicly-funded programmes at a number of different career levels (graduate student, early postdoctoral researcher and beyond). We then discuss issues of graduate supervision, mentoring early career researchers, and the advanced training and development activities that may be required to develop future interdisciplinary research leaders and help them make the transition between the various career stages.

Other authors have addressed many of the more methodological issues encountered in designing and conducting interdisciplinary research at the graduate level (for example, [18–20]). Nash [21] recommends 'meta training' to help early career researchers understand and manage distinctive features of their own interdisciplinary education, future work and careers, suggesting that necessary knowledge and skills are best developed through a mix of 'formal didactics, research experiences, and mentorship'. Here we consider what other forms of support may be required in terms of advanced training and career mentoring in order to develop the next generation of interdisciplinary researchers and improve the experience of the current generation. This is especially important in order to build interdisciplinary

communities, often spanning multiple networks, as interdisciplinary scholars do not readily develop the same types of 'invisible colleges' as their monodisciplinary peers.

2. Building interdisciplinary capacity: some challenges

Disciplines, or perhaps more accurately sub-disciplines or schools of analysis, have resulted in stable systemic communities within which researchers concentrate their experience into a particular worldview. This has benefits in terms of the efficiency of communication and interaction within the disciplines (including, for example, assessment of quality or the verification of knowledge claims) but puts limits on the kinds of questions they can ask about their material, the methods and concepts they use, the answers they believe and their criteria for truth and validity [22].

We have witnessed the re-engineering of academic disciplines in the life sciences, with the emergence of new fields such as synthetic biology, for example, involving teams of researchers with a wide range of disciplinary skills. However, other disciplinary combinations – in particular those required to address research questions that span the social and natural sciences – can be much more challenging and there can be real challenges in forging synergies across seemingly distant disciplines. Whereas Abbott ([23] p.136) describes 'a structure of flexibly stable disciplines, surrounded by a hazy buzz of interdisciplinarity' (i.e. disciplines in a constant state of flux but ultimately little radical change), others note that 'disciplines do not keep up with rapid developments in modern societies' so that the 'map of knowledge...is always outdated' ([24], p.29). Interdisciplinary interactions are clearly transforming the natural sciences and the social scientists who work with them. Some social scientists believe that working with cognate disciplines in the social sciences may, in fact, be more difficult than working with natural sciences [25]. The social sciences often have a stronger focus on method and this may give the impression that they are more discipline-bound than the natural sciences: different methods can either open up or close down the possibility to ask different sorts of questions. One of the explanatory factors may be that the social sciences often emphasise a certain body of knowledge which reinforces disciplinary differences: there may be particular problems among the social sciences where competing methodologies are brought to bear on the same research topic (*ibid.*). Natural scientists may be more oriented around the fluidity of experimental activities and the sharing of techniques. Among the natural sciences there may be more experience of the benefits to disciplines from interdisciplinary collaboration, for example in terms of the evolution of new disciplines such as materials science in the 1980s and, as noted above, synthetic biology in the current decade.

The seven UK Research Councils (covering medicine, biology and biotechnology, engineering and physical sciences, natural environment, arts, humanities, and social sciences) are increasingly joining forces to tackle these challenges by funding schemes that seek to foster interdisciplinary research skills in 'next-generation researchers'. The Economic and Social Research Council (ESRC) has identified interdisciplinary, collaborative research to be a key means of addressing major social and economic challenges [7] and its Postgraduate Training Framework [26] also highlights better opportunities for interdisciplinary training programmes, supporting the long term ability of the UK social science community to address complex research questions.

However, interdisciplinary training is by no means a mainstream activity in UK universities and there are still gaps in our collective understanding of how capacity-building in interdisciplinary research expertise can be achieved. Despite attempts to promote interdisciplinary research and collaboration between different natural sciences and between

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the social and natural sciences, or with the humanities, evidence suggests that existing capacity-building schemes do not yet offer the growing number of early-stage interdisciplinary researchers sufficient opportunities to network and share learning about the considerable intellectual and management challenges of interdisciplinary research [15,16].

Nor should graduate students be the sole recipients of such training; continuous interdisciplinary skills development is also valuable and necessary: many mid-career researchers may find themselves suddenly involved in or indeed leading interdisciplinary work, having been provided with no advice on how to do it well. There needs to be recognition of research – and interdisciplinary research in particular – as a craft that needs to be learned through practice. In addition to traditional face-to-face short courses and annual summer schools, this may include less conventional types of training such as ongoing mentoring to impart skills and work-shadowing or placements in research settings [27].

In the US, the situation may be a little different. With a much longer tradition of inter- or at least multi-disciplinary undergraduate curricula and a different degree structure, American university students tend not to specialise as early as those in the UK. Nevertheless, we share many common challenges when supporting interdisciplinary research capacity (see for example, [9]) and US funders are also finding non curriculum-based approaches to supporting early stage interdisciplinary researchers such as the Dissertation Proposal Development Fellowship (DPDF), offered by the US Social Science Research Council¹.

Many commentators, from both sides of the Atlantic (for example, [17] [28]), have called for radical changes in the ways in which interdisciplinary scholars of the future are trained. One such approach is the Integrative Graduate Education and Research Training (IGERT) scheme of the US National Science Foundation. This is a publicly-funded programme that provides large-scale grants to individual institutions to develop postgraduate training in a particular interdisciplinary area (e.g. language sciences) with the goal of building interdisciplinary human capacity.

One of our findings from the Masterclasses, described below, and from our own evaluation of a UK interdisciplinary studentship scheme [15], is that graduate students undertaking an interdisciplinary PhD can often feel rather isolated unless they are based with like-minded individuals in a centre or department that specialises in interdisciplinary research. The IGERT scheme entails broad programmes within institutions and this seems to address some of the difficulties encountered by more scattered individuals.

Interdisciplinary research can engender concerns about the loss of quality within individual disciplines but this has not been an issue for the IGERT scheme: for example, 84% of IGERT faculty felt that their students 'are being prepared to know their own discipline in depth' well or very well. There was also a positive view as to career possibilities, with 63% of IGERT students surveyed feeling they were being prepared for a wide range of career possibilities, compared to 44% of non-IGERT students [29].

Our analyses of UK-based interdisciplinary studentship and fellowship schemes [15,16] have identified the importance of developing a variety of mechanisms for fostering interdisciplinarity among early career researchers (ECRs) funded by such schemes. When surveyed, IGERT students similarly selected mechanisms such as access to expertise and experience outside of their home discipline through conference attendance and laboratory rotations in multiple disciplines [29].

¹ www.ssrc.org/fellowships/dpdf-fellowship

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Our evaluation of the ESRC-MRC scheme [16] showed that nearly all supervisor/mentor respondents agreed that they had either to some or a great extent furthered their own interdisciplinarity, with more than half having developed other interdisciplinary collaborations. Showing a similar 'ripple effect', the IGERT evaluation also found that participation in IGERT led to 'an additional shift towards more interdisciplinary work' as reported by academics and department chairs [29].

As former students of the scheme, Graybill et al. [30] offer reflections of the Urban Ecology IGERT and put forward six recommendations for both students and institutions undertaking interdisciplinary research and training programmes:

- attend to the processes involved in simultaneously exploring interdisciplinary topics while also addressing the interpersonal dynamics of the groups involved
- develop students' sense of ownership of the programme
- garner institutional support, both intellectual and financial
- plan for your own progress in order to successfully complete an interdisciplinary doctorate
- create and maintain flexibility regarding logistical issues such as scheduling
- practise appreciative inquiry in order to understand and appreciate different worldviews

Many have discussed how the dominant structures and norms within universities and doctoral education make it difficult to conduct interdisciplinary research (for example, [17]). The same is also true when developing interdisciplinary capacity within the wider research community. Is it better to approach these interdisciplinary research capacity-building challenges in a way that builds from and across the different disciplinary/substantive bases [27] or to adopt a more generic approach that recognises that many of the research design, development and management issues are universal and largely independent of the particular research topic being addressed? We have attempted to do both with a series of capacity- and community-building activities which we will now describe.

3. Our response to these challenges

Much of the knowledge that surrounds interdisciplinary research capacity-building is tacit, with practitioners often 'learning by doing' through a process of informal apprenticeship with more experienced colleagues who may not always articulate or explain the good practice they are conducting as a matter of instinct. In this section we will describe how we have sought to formalise and codify our approach to interdisciplinary research and to share this knowledge around how to design, manage, report and evaluate interdisciplinary research with the research community.

Through our extended engagement with these interdisciplinary research challenges we identified two skills gaps in the UK. The first was at the graduate level where PhD students in the social sciences are generally taught about a range of qualitative and quantitative research methods and given the tools with which to construct the research design for their thesis. However, unless students are embedded in a centre specialising in interdisciplinary research, those engaged on interdisciplinary projects are rarely given any specialist help with their research design and are presented with the considerable challenge of drawing on, and integrating, two or more bodies of literature and methodologies and indeed research paradigms. The second, related challenge occurs at a later stage in researchers' careers when they are faced with leading an interdisciplinary research team for the first time. This

can require a particular set of skills which we believe are not extensively taught at present and are, again, essentially 'learned by doing'.

The origins of this approach lie in our evaluation of the ESRC-NERC interdisciplinary scheme [15]. A very strong recommendation of our report (supported by 90% of awardholders surveyed) was to bring students together to share experiences, challenges and lessons learned regarding interdisciplinarity. Supervisors also supported this shared learning in order to reinforce students' confidence and abilities as interdisciplinary researchers. We thus developed a range of masterclasses – the ISSTI Interdisciplinary Masterclasses² – at two levels. The first was aimed at graduate students embarking on interdisciplinary projects for the first time and sought to improve students' ability to design interdisciplinary research projects and give them a better understanding of the issues and challenges of interdisciplinary research spanning the natural and social sciences. The second level aimed to provide new 'interdisciplinary integrators' at the postdoctoral and junior researcher stage with the tools they require to lead successful interdisciplinary project teams in order to develop participants' research management, leadership and supervisory skills in interdisciplinary projects across the social and natural sciences. Some of the teaching materials we developed for these courses have also been used in other training contexts and made available to the wider research community via a project wiki³. We have, more recently, adapted these workshops for more senior researchers, research managers and administrators.

These workshops went beyond the usual training in transferable research skills and developed a virtuous training circle: those trained to be interdisciplinary integrators will incorporate their interdisciplinary research management skills into their supervisory roles, thus helping the next generation of researchers to adopt good interdisciplinary practice in their research design and project development. By recognising that different gaps exist at different levels, we were able to develop a systematic approach to imparting often intuitive, craft-based skills.

The programmes for the Masterclasses consisted of training activities along with an element of sharing of research experiences which we hoped would develop into lasting peer networks useful to interdisciplinary researchers throughout their careers. The Masterclasses examined the motivations for interdisciplinary research and the different modes of interdisciplinary working, in particular one of the most challenging forms of interdisciplinary engagement – the direct involvement of social scientists as collaborators in scientific and technological research.

The graduate Masterclass focused on issues to do with research design and writing an interdisciplinary thesis. The postdoctoral Masterclass focused on developing in junior and mid-career academics the skills needed to be a good interdisciplinary researcher and research manager or leader of interdisciplinary teams. These included the need to understand the languages, research methods and cultures of different disciplines, as well as to appreciate the way that interdisciplinary research often cuts across systems of reward and resource allocation found in most universities. These workshops addressed the various goals of interdisciplinary collaboration, the ways in which it may be sustained, the problems that may be encountered in interdisciplinary careers and tactics for addressing such challenges.

² ISSTI is the Institute for the Study of Science, Technology and Innovation at the University of Edinburgh. The Masterclasses were funded by a grant from the UK Economic and Social Research Council RES-035-25-0001.

³ www.tinyurl.com/idwiki.

The workshop programmes broadly addressed:

- sharing of problems and lessons learned about the pursuit and timely completion of an interdisciplinary PhD (including the role of supervisors)
- development of publication strategies
- networking to become part of a community
- marketing oneself for posts while maintaining one's interdisciplinary approach
- career advice (career path challenges facing interdisciplinary junior academics, awareness of non-academic jobs and potential applications of research to policymaking and other stakeholder areas)
- understanding different languages, methods, cultures
- variety of motivations for, and different modes of, interdisciplinarity
- maintaining an interdisciplinary approach within discipline-focused institutions and academic reward mechanisms
- common interdisciplinary research management challenges

In each case, trainers drew on examples from their own research across a range of disciplinary and interdisciplinary domains spanning the natural and social sciences. Examples of such interdisciplinary work spanned the life sciences, information and communication technologies (ICT), energy, environment and design sectors and we sought to complement generic messages about interdisciplinarity with concrete lessons about its application in range of 'real' research and policy contexts. Masterclass participants were working on a wide range of research questions from an evaluation of ICT in healthcare (a project which drew on computer science, medicine, medical sociology, psychology and epidemiology) to social learning about water resource management (combining geography, sociology, psychology and environmental science).

These activities took the form of advanced training rather than curriculum-based teaching and we adopted a residential, workshop-based format. The programme included a number of guest lecturers but focused on interactive training methods, small group working structured around readings (either short published articles or scenarios that we had written ourselves), and plenty of informal discussions in a social setting. Participants greatly valued the opportunity to network and learn from others' experiences. Feedback from the first event (aimed at graduate students) showed that 82% of participants had thought about interdisciplinarity in at least one new way as a result of the Masterclass and 77% had at least one new insight into overcoming the challenges of an interdisciplinary PhD. In a follow up survey a year later, almost a third had changed something about their research as a result of the Masterclass and almost a quarter acknowledged that they would benefit from further interdisciplinary training as their career progressed.

How successful was this small-scale initiative in achieving its goals of building and consolidating interdisciplinary skills and mobilising a relatively new and growing research community in the UK? The events were certainly oversubscribed, with demand outstripping our ability to supply enough events within the allocated budget. The Masterclasses and related activities have clearly demonstrated a demand for this type of advanced training and community-building within (at least) the UK context given the stage of development of interdisciplinary research capacity. Early career researchers (and some of the more established researchers who participated) benefited from help in stepping back and learning about the processes involved in interdisciplinary work and the implications for their university careers. They also seemed to appreciate the sense of community that can be stimulated by this type of activity.

One of the outcomes from these workshops has been a series of guidance notes⁴ written in association with workshop participants, in particular the postgraduate students, who were able to share practical advice for mentoring and supervising interdisciplinary early-career researchers which we draw on in the remainder of the paper.

4. Reflecting on aptitudes for interdisciplinary research

It is clear that interdisciplinary capacity building is not simply a case of teaching single methods or research techniques. Instead, it is about cultivating a range of cognitive skills (such as differentiating, reconciling and synthesising) and promoting interpersonal and intrapersonal learning that will foster an ability to respond to complex questions, issues or problems ([31] cited by [32]). In developing such abilities we may well be striving to achieve 'pursuit of a conversation aimed at enhanced understanding rather than victory for one point of view' [20].

Lau and Pasquini [28] speak for many when they describe the practical obstacles facing interdisciplinary scholars and the 'common struggle to find a disciplinary niche' or negotiate an identity, not least because the boundaries of interdisciplinary research are under constant negotiation. These authors discuss how 'the expectations, attitudes, and approaches of researchers, and their very conceptualising of interdisciplinarity, are all influenced by their personal backgrounds to a considerable degree, although the extent of this influence may be neither noticed nor acknowledged', an aspect they term 'positionality'. From this they argue that, the fact that the definition of interdisciplinarity is necessarily under constant debate, may be in large part due to the myriad 'positionalities' of spectators of, and actors in, interdisciplinary research. Even committed interdisciplinary scholars fail to recognise the degree to which their academic positionalities (including in the case of the geographers they studied: specialism, age, training and possibly gender and seniority) affect their stances to, and understandings of, interdisciplinary research [28].

Effective interdisciplinarians need to be more proactive than those scholars operating within established communities: they need to develop strategies for managing their positionality in terms of building networks of reputation and collaboration as well as strategies for portfolios of different types of publications. Moreover, good interdisciplinary supervisors and mentors are likely to be open-minded, willing to learn from other disciplines and have a broad appreciation for the languages, research methods and cultures of different disciplines. In many ways, personality may be more significant than discipline base: interdisciplinary supervisors are likely to have a high degree of curiosity beyond the boundaries of their own discipline so there is little point in taking on an interdisciplinary student if one has no interest in the other contributing discipline(s). The Masterclass format has encouraged self-reflection and discussion on aptitudes for interdisciplinary work and supervision.

5. Supervising an interdisciplinary PhD

Interdisciplinary research is not a single, homogeneous entity but takes different forms depending on the research question. Interdisciplinary research can be within the social sciences, within the natural sciences or between the social and natural sciences and/or humanities. Distinctions can also be drawn between long-term, interdisciplinary involvement for 'academic' reasons (e.g. to enable a discipline to move into new areas of research) and the more instrumental, situational interest where the primary aim is problem-oriented and discipline-related outputs are less central to project design or, put another way, the contrasts

⁴ Available from www.tinyurl.com/idwiki

between the 'scholarship of discovery' and the 'scholarship of integration' ([33], p. 263). We have previously characterised these different approaches [13] as:

- research which aims to further the expertise and competence of academic disciplines themselves, e.g. through developments in methodology which enable new issues to be addressed or new disciplines or sub-disciplines to be formed (*academically-oriented interdisciplinarity*)
- research which is problem focused and addresses issues of social, technical and/or policy relevance with less emphasis on discipline-related academic outcomes (*problem-focused interdisciplinarity*)

These two models of interdisciplinary research are appropriate to different types of research questions and the criteria for the choice of disciplines to be involved in a project will also differ in each case. The research may even represent a mix of the two modes. Those new to interdisciplinary supervision may wish to learn more about the different modes of interdisciplinary research and identify which mode of interdisciplinarity applies to their student's research in order to help them think through the implications for the research design and the nature of supervision. For example, if the research tends more towards academically-oriented interdisciplinarity, the supervisor may wish to find co-supervisors who are also working in that emerging sub-discipline. If the research is to be more problem-focused, the supervisor may need to help the student ensure that the thesis has a sufficiently theoretical grounding to satisfy the traditionalists.

In the next sections we discuss in more detail the various stages and aspects of supervising an interdisciplinary PhD: developing a supervisory team; framing, structuring and writing the thesis; and integrating the student into appropriate research networks⁵.

5.1. Developing and maintaining a committed supervisory team

Supervision is an important aspect of any PhD project, but the complexities of interdisciplinary research make appropriate supervision even more important. Close supervision and guidance are particularly important for interdisciplinary students in order, for example, to encourage genuine integration and prevent students from slipping back into monodisciplinary comfort zones. On the other hand, supervisors need to be open to the really smart student who knows exactly what he/she wants to do, is very capable, and will respond best to light-touch supervision.

Given the range of subject matter to be covered, it is common for interdisciplinary PhD projects to be supervised by a team where individuals have different disciplinary strengths. This does not, of course, preclude the supervisors themselves being interdisciplinary researchers. Supervisors need to develop strong team-working with co-supervisors if students are to benefit rather than suffer. Supervisors, co-supervisors and students need to meet regularly, with sufficient clarity and continuity of communication, that such issues as methodologies, format and focus of the thesis, are agreed mutually and explicitly at an early stage and that inevitable fine-tuning of the developing thesis takes place through ongoing dialogue.

⁵ A checklist of some of the do's and don'ts of interdisciplinary supervision and mentoring that we have identified through our work with early career researchers is available from www.tinyurl.com/idwiki.

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Care needs to be given to the selection of co-supervisors (or PhD committees in the US) in terms of collaborative compatibility as well as ability to commit to regular meetings with the whole team. More so than monodisciplinary supervision, the commitment of the secondary supervisor(s) is crucial: they are not simply nominal appointments but should bring complementary, discipline-based expertise and networks to the project. (The larger PhD committees in the US may lend themselves more readily to mixes of perspectives and expertise, but even so care needs to be taken not to include overly traditionalist views that might seek to restrict the research design or execution.)

The lead supervisor should facilitate an initial meeting between all parties. It may be helpful to ask each supervisor to bring copies of their key publications and for the student to bring a summary of their Master's thesis and outline PhD proposal to begin to foster some shared understandings of each other's work. It may be helpful for the supervisors to hold occasional 'pre-meetings' to discuss their common response before key meetings with the student.

5.2. Building foundations and setting boundaries

Disciplines have survived for so long in the academic world in part because they serve the very useful function of constraining what the researcher has to think about. They set a boundary on the parameters of interest (what to include and what to leave out) and dictate the range of methodological approaches that are relevant. They thus provide a clearly defined starting point for a project. In interdisciplinary research, where this framework is partially or wholly removed, students can be overwhelmed by the resulting complexity. A key role for supervisors is therefore to help the student set some boundaries to their research while achieving an appropriate balance between breadth and depth. By definition, interdisciplinary students will not be specialists – and they should not feel as if they are failing because this is true; they cannot try to become experts in all fields involved.

More than monodisciplinary projects, interdisciplinary research has to initially test out a range of possible boundaries to the problem to see which gives the best 'fit'. This should be part of the process of developing a research proposal. It should be clear that the outcome represents a justifiable decision on the project's boundaries. An interdisciplinary student may require particular help in framing a research question that is manageable, suitable, and reflects their interests. This will require discussion with all supervisors to agree the level and scope of the research and, in particular, realistic timescales.

5.3. Structuring and writing an interdisciplinary thesis

Students must for their survival (and successful completion) stay focused, knowing what part of which disciplines they will use to answer which research questions. Despite the frequent association of interdisciplinarity with "creativity" and frontier-crossing, more planning is likely to be needed for interdisciplinary projects than for disciplinary projects.

There are different conceptions of what constitutes a PhD thesis: the natural sciences classically have a greater focus on publishing papers, so that each thesis chapter may correspond to a paper, whereas a social science thesis more usually resembles a monograph. Interdisciplinary students need to be given early guidance on whether to follow such a route or develop a distinctively interdisciplinary approach. Extra effort is needed to promote the formation of a cohesive thesis that combines inputs from several knowledge domains. An active strategy is thus needed to integrate the different disciplines and different models in an interdisciplinary project. To this end, supervisors need to encourage integrated rather than 'compartmental' writing. In order to achieve this, at least one member of the

supervisory team needs to commit to reading everything that the student writes and ensuring that the student is writing in a way that is accessible to readers (especially examiners) from all contributing disciplines.

5.4. Building an interdisciplinary network

Supervisors wield considerable influence over the student's early professional life and play a key role in 'socialising' the student [17]. An important success factor for an interdisciplinary student is the development of an interdisciplinary research network but students may have a strong incentive to follow the research direction set by the supervisor: depending on the supervisor this may reinforce disciplinary specialisation [17]. Cross-discipline meetings, seminars, etc. will help the student to build interdisciplinary networks. An interdisciplinary supervisor therefore has an important role to play in helping the student to identify appropriate workshops, conferences and other networking opportunities both within and beyond their own institution. This is likely to require extra effort when the default approach of a supervisor might be to introduce a student to the community of just their own discipline.

A vital part of the supervision process is the early identification of appropriate examiners, who will be sympathetic to the interdisciplinary approach. This is likely to require more careful consideration and may need to be started at an earlier stage than for a monodisciplinary student.

5.5. Developing a publications strategy

Early career researchers need to pay particular attention to publication. In the UK, the tendency of the Research Assessment Exercise (and, as seems likely, its successor the Research Excellence Framework) to favour single-discipline quality indicators by structuring assessment around disciplinary sub-panels has, in the past, made it more difficult for interdisciplinary researchers to publish their work in high quality outlets as these are more often regarded by reviewers and editors as having a monodisciplinary focus (for example, [34]).

This means that interdisciplinary researchers – and especially those at the early stages of their career – need a publications strategy that encompasses both interdisciplinary and more conventionally esteemed monodiscipline journals. This may mean that interdisciplinary students have to be more creative in order to publish in a range of well-regarded journals. Supervisors therefore need to encourage interdisciplinary students to plan a strategic portfolio of different types of articles: theoretical, interdisciplinary, policy, etc. Moreover, interdisciplinary work may require more time to reflect on the potential connections between different aspects of the research. It may be harder for interdisciplinary students to publish during their doctoral studies than, say, monodisciplinary students in the natural sciences whose work may be part of a team-based research project leading to earlier publication opportunities with more experienced members of that team.

6. Mentoring and career guidance

Part of any supervisor's role is to promote the student's personal and academic growth into a mature and independent researcher. This may involve assisting the student in structuring their own research ideas and exploring interdisciplinary career opportunities. It may be appropriate to encourage career development activities (e.g. teaching experience) provided that this does not interfere with the student's ability to complete their PhD thesis in a timely fashion. Interdisciplinary students may need particular guidance with time-management:

interdisciplinary theses may typically take longer to complete given that students need to read across different bodies of literature, possibly learn multiple research methods and wrestle with the issues of integration.

Long-term research collaborations begin to develop at this stage in a researcher's career and are built upon a strong foundation of communication and mentoring. Before embarking on such a professional relationship, early-career researchers should be encouraged to ask themselves some fairly searching questions about the benefits of such a partnership. For supervisors and mentors further consideration might be given to offering mentoring opportunities (either with senior colleagues or peers) to give junior staff an opportunity to share experiences, career development plans, etc. As these early career-researchers will very rapidly become mentors and supervisors themselves, some training in supervising and examining interdisciplinary PhDs may also be welcome.

As interdisciplinary research often involves working with research users outside of academia, early-career researchers may benefit from communication training in order to target their language to different audiences and reach a range of different stakeholders and research partners effectively. Training in interpersonal skills such as facilitation, stakeholder engagement and mediation may be particularly valuable for interdisciplinary researchers.

7. Conclusion

Disciplines place boundaries around bodies of knowledge. This confers many advantages: it facilitates efficient teaching and provides guidance on research norms (such as an essential set of standards, an established way of framing problems, key theories and methods) but the model of the lone scholar working in one narrow discipline is now much less common. We have seen through the work of Gibbons et al. [35] and Nowotny et al. [36] that a dynamic is emerging between discipline-based and interdisciplinary research. Others argue for a 'third wave of interdisciplinarity' where contemporary knowledge production involves, not only a horizontal axis stretching across academia, but also a vertical axis integrating academic research into society [37].

But effective interdisciplinary working does not "simply happen"; it calls for greater reflection – and greater effort – by those involved. As well as the obvious barriers to communication between different specialisms, university-based interdisciplinary researchers will encounter institutional barriers (departmental structures, management systems, reward mechanisms) that are most often based around disciplines. Interdisciplinary researchers therefore need to plan their future career pathways and personal development more carefully than academic colleagues with more traditional career paths. They may consequently need better mentoring both from immediate supervisors and line managers but also at an institutional level so that they both respond to sponsors' requirements but also think strategically about their own personal research and publication strategy.

We know that financial incentives are important but not sufficient to cause lasting change within institutions [2]. These challenges also need to be addressed at higher institutional and policy levels – both at the level of research funders and senior university research leaders and managers – if individual researchers and centres are to build effective and successful programmes of interdisciplinary research. In particular, tackling some of these issues may also require institutions to develop greater research leadership in order to grow the necessary talent to populate research teams with experienced, interdisciplinary researchers who can, in turn, nurture interdisciplinary research capacity in future generations. Short, focused learning experiences such as workshop-based 'masterclasses'

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of the type described in this paper can enhance effective interdisciplinarity and contribute to the development of mutually-reinforcing networks and research communities.

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